Ground Mobility Systems for Planetary Exploration

Paolo Fiorini

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91109

Abstract: *This paper surveys past and current designs of surface mobility systems for planetary exploration robots developed at JPL/Caltech. Wheeled rovers are discussed in some detail, and compared to new designs, such as legged and hopping robots, which are emerging as viable alternatives to wheeled mobility for specific applications. The paper discusses the main features of mobility designs and summarize some of the experimental test results.*

1 Introduction

In spite of the occasional setbacks, the exploration of the Solar System is progressing towards its major objective of returning samples of Mars rocks and sand to Earth within the next decade during the Mars Sample Return missions. However, new types of mobile robots, as well as new exploration paradigms are needed to advance the Solar System exploration. In particular, great emphasis must be given to those solutions expanding range and flexibility of next generation robots.

So far, the only paradigm used in planetary exploration is the multi-wheeled rover demonstrated by Pathfinder mission's *Sojourner* vehicle [10]. To address the needs of the Mars Sample Return missions, rovers with manipulation capabilities have been developed, able to drill rocks, scoop dust, and pick up small pebbles. such as JPL Rocky 7 [18] and FIDO [13]. Furthermore, rover with larger, inflatable wheels are proposed to negotiate larger rocks [8], whereas smaller rovers, will be used to explore difficult areas, such as Mars mountain cliffs, or low gravitational environment, such as asteroids and comets [20]. Legged rovers have also being proposed for Lunar and Martian exploration [1] and for orbital maintenance. However, both wheels and legs do not complete solve the accessibility problem, and involve a significant design complexity. Thus, a new generation of minimally actuated devices capable of moving a small science package by hopping is also being developed [7].

The paper describes in some detail the main features of the robotics devices mentioned above, presents some of the design trade-offs and summarizes a few significant experimental results.

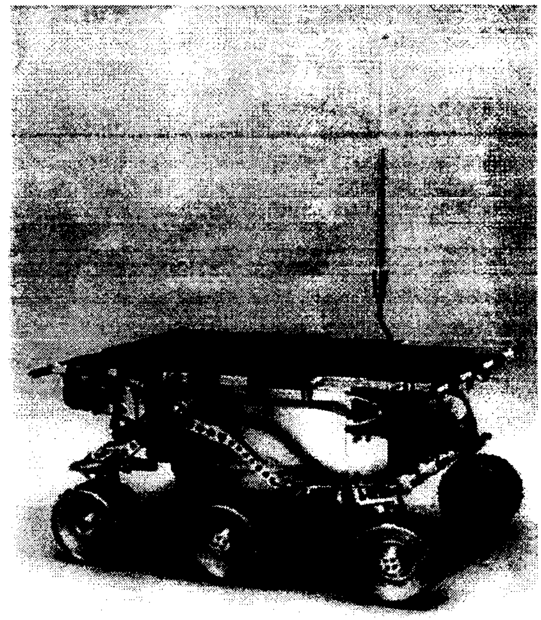

Figure 1: The Sojourner-class Mars Rover.

2 The First Generation

During Summer 1996, a pair of twin devices completed environmental and functional tests. One of them was called Sojourner and took off for Mars, while the other remained at JPL as the simulator for command sequences during the course of the Pathfinder mission. This rover, now called Marie Curie, will be launched on March 2001 to explore Mars equatorial areas. The two rovers are substantially identical, except for a few modification resulted from Sojourner experience [6].

The design of the rovers has been influenced by a wide range of mission, environmental, and programmatic constraints. These have forced the design of a vehicle whose characteristics are summarized in Table 2, and shown in Figure 1 [15]. Since this mobility design is common to all JPL wheeled rovers, a detailed description is warranted. Mobility is achieved by a 6-

Dimensions (cm)	68(l) × 48(w) × 28(h)
wheel diameter	13
ground clearance	16
Mass Total (kg)	10.5
Power Requirements (W)	10
Max Speed (cm/s)	10

Table 1: Sojourner main mechanical parameters.

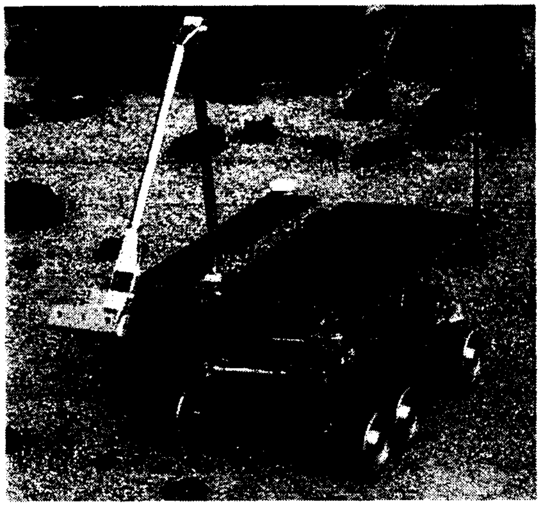

Figure 2: The Rocky 7 research rover.

wheel drive, 4-wheel steerable rocker-bogie suspension system [3]. This design consists of two pairs of rigid linkages, one on each side of the rover, connected to one another by a passive rotary joint. The front and middle wheels are rigidly attached to each end of the forward linkage, the *bogie*. The rear wheel is attached to the rear end of the rear linkage, the *rocker*. Of these three wheels, the two external ones are steerable, providing direction control and turn in-place. The forward end of the rocker is attached to the middle of the bogie through a rotational joint. The rocker-bogie assembly is attached to the chassis by means of a rotary joint located in the middle of the rocker. The two rockers are connected to each other and to the chassis on the rear of the vehicle, by a transversal link creating a differential between the two sides of the vehicle. As the vehicle drives, the wheels are free to move up and down independently of one another and to follow the contour of the terrain. The kinematics of the design are such that the weight of the vehicle remains nearly equal across all six wheels. Testing has verified that the vehicle can safely climb obstacles 1.5 wheel diameters in height.

Rover navigation is achieved by a combination of operator-based way-point designation [22] and on-board behavior control [5]. Way-points are selected

Dimensions (cm)	61(l) × 49(w) × 31(h)
wheel diameter	13
arm reach	33
ground clearance	16
Mass Total (kg)	11.5
Power Requirements (W)	48
Max Speed (cm/s)	30

Table 2: Rocky 7 main mechanical parameters.

on Earth based upon the interaction among scientists and operation personnel. A collection of viewpoints determines the rover path, and it is the responsibility of the human operator to select paths which are free of dangerous obstacles. The behavioral component of the navigation control is responsible for autonomously and safely guiding the vehicle from one way-point to the next [11]. These algorithms enable the rover to respond in real-time to terrain uncertainties and to choose the appropriate avoidance strategy of obstacles which were undetected by the operator.

3 The Current Prototypes

Next rover exploration of Mars will be focused on the activities related to Mars Sample Return [19]. Two Mars missions will be devoted to this task, launched on March 2003 and on August 2005, respectively. According to current schedule, samples collected by the two missions will be placed on Mars orbit on July 2004 and July 2006, then retrieved by the 2005 orbiter, and returned to Earth on April 2008. The flight rover has been appropriately named *Athena* and a ground prototype, *FIDO* (Field Integrated Design and Operations rover), is currently undergoing extensive tests. FIDO is the pre-flight version *Rocky 7*, the latest of JPL research rovers shown in in Figure 2.

Table 3 summarizes the main characteristics of Rocky 7. It has the same number of degrees-of-freedom (DOF) of Sojourner, but with more functionality. Figure 3 shows the wheel configuration used in this prototype. Like the first generation rovers, Rocky 7 employs a rocker-bogie six wheel configuration, but steering is only on two corners, like a car. This allows the reduction of the mobility DOF's from ten to six, losing the ability to turn in place, but gaining four DOF's for manipulation. The lack of turn-in-place capability forces the rover to use a new approach to navigation when it enters a deadend alley. In this case, the rover retreats autonomously the length of the path and resumes its forward navigation when it detects that it can make a turn.

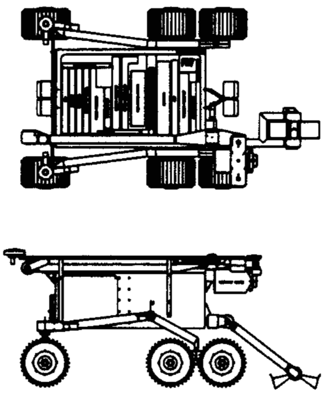

Figure 3: Drawings of Rocky 7 mobility mechanism.

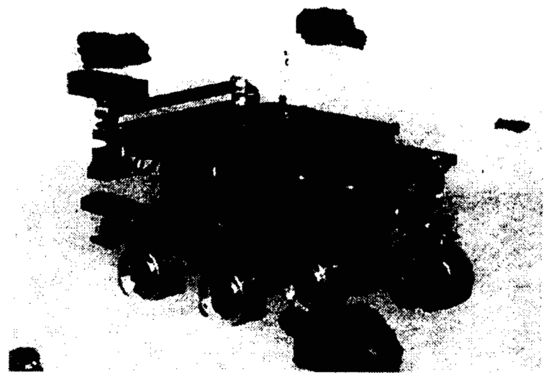

Figure 4: Fido overcoming a rock.

Rocky 7 has been extensively tested outdoors, at JPL *Mars Yard* test facility, and during field tests in the desert. The Mars Yard is a 15 × 25 meter outdoor test area populated with rocks having the same density distribution of typical Mars terrains.

Desert tests were performed at Lavic Lake, a lava flow and dry lake-bed on the Twenty Nine Palms Marine Corps Base, and consisted of traversing more than one kilometer across several different terrain types [17]. Performance comparison among three different rover types (Rocky 3, Sojourner, and Rocky 7) [17] indicate that navigation differences are mostly due to rover sensors, with a small contribution due to wheel slippage. Thus normalized performance of different power trains, number of drive wheels, and steering mechanisms seem to have a negligible impact on rover navigation capabilities.

Table 3 summarizes the mechanical characteristics of the rover FIDO. The mobility sub-system for FIDO is a six-wheel, rocker-bogie configuration which is geometrically scaled by a factor of 20/13 in proportion to the analogous Sojourner rover configuration. All six wheels are driven and steerable for increased rover maneuverability. A differential joint internal to the rover's chassis couples each side of the rocker-bogie to the rover chassis. Each wheel is actuated by a motor capable of 35 N-m torque/wheel at stall. Sensors for the mobility sub-system include optical quadrature encoders for all drive wheels and optical quadrature encoders and potentiometers for all steered wheels. Hard stops prevent over-travel of rocker and bogie links. Potentiometers are also integrated into the rocker-bogie structure so that the position of each bogie arm with respect to the rocker arm are known. The rocker arm position with respect to the chassis is known through a geared potentiometer located at the internal differential. FIDO carries a 5 DOF (4 active degrees and 1 passive degree) instrument arm and a 4 DOF mast used to acquire panoramic images. The rover carries four stereo camera pairs for navigation and a CCD-based sun-sensor to measure rover heading. Navigation is continuous using on-board computer vision and autonomous control. FIDO was recently tested in a simulation of the Mars Sample Return mission in the Mojave Desert at Silver Lake (CA) a site replicating some of Mars geological features. These tests demonstrated a complete sequence of imaging, autonomous navigation, observation, and sample acquisition.

Dimensions (cm)	110(l) × 97(w) × 53(h)
wheel diameter	20
arm reach	194
ground clearance	23
Mass Total (kg)	61.8
Power Requirements (W)	100
Max Speed (cm/s)	9

Table 3: FIDO main mechanical parameters.

4 Smaller and Larger Rovers

To enable the exploration of difficult terrains and to increment the exploration speed, rover design has evolved two different families of devices: a smaller one, called the *Nano* rovers, and a larger one using *inflatable* wheels.

The nano-rover prototype has a four-wheel mobility system with wheels on movable struts, as shown in Figure 5. Each wheel and strut can be positioned independently to control the robot pose, and each wheel is independently actuated enabling turn-in-place. The mobility mechanism allows the nano-rover to pose its body to achieve a variety of configurations that facilitate pointing instruments, operate upside-down, self-right, and run low to the ground on slopes or under barriers. Solar cells are placed on all sides of the rover so that it will always have enough power to actuate the motors. However, the existing research prototype is battery-powered. Navigation control is tailored after Sojourner's. It implements a top-level control loop that autonomously executes single commands, or com-

Figure 5: The nano-rover prototype.

mand sequences, uplinked by a remote operator. An underlying substrate of primitive motion behaviors enables point-to-point navigation, body articulation, and instrument pointing [16]. Table 4 summarizes the main parameters of the nano-rover.

Proposed applications of the nano-rover include cliff and asteroid exploration. In the first case, the nano-rover would be connected to a larger rover by a tether, providing mechanical support, as well as power and communication. Mobility analysis on low-gravity asteroids indicates that tractive forces will be sufficient for surface exploration of low-gravity bodies [2]. The nano-rover will be part of a mission aimed at reaching the small near-Earth asteroid 4660 Nereus, which has a diameter of about two Km and a gravity field estimated to be about 100,000 times weaker than Earth's [21]. The spacecraft will arrive at the asteroid in April 2003, using a new solar electric propulsion system. The rover's task will be to move around the surface of the asteroid collecting images. The imaging system can measure surface texture, composition and morphology with spatial resolution better than 1 millimeter. The rover will transmit these data to the spacecraft for relay back to Earth.

Since most wheeled rover can only drive over obstacles that are at most about 1.5 times their wheel diameter, inflatable larger wheels may be able to overcome proportionally larger obstacles. This consideration has led to the development of large rovers equipped with inflatable wheels, as shown in Figure 6. These devices are

Figure 6: The inflatable-wheel rover prototype.

currently proposed for a variety of applications, from navigation in rough terrains, since low pressure wheels will compensate for terrain asperities, to climbing steep slopes (up to 30^o), to amphibious missions on Titan, one of Saturn moons, for land and sea exploration with a single vehicle. Table 4 summarizes the main parameters of this rover prototype.

5 Legged Rovers

Since difficult terrains, such as steep cliffs or rock fields, are inaccessible to most wheeled rovers, legged rovers are getting some, albeit small, attention from space mission planners. In the last couple of years, two proof-of-concept have been developed at JPL, showing the feasibility and the possible advantages of a legged rover.

The Mars Hexabot system, called *Henry-99*, is designed as a surrogate "field geologist" to survey the Martian terrain and identify interesting areas. The mobility concepts part of this prototype include science sensors integrated in the footpads, and energy storage legs for the efficient traversal of flat terrain at relative high speed. The second prototype, called *LEMUR*, is a hexabot device designed for demonstrating robotic servicing of a Space Solar Power Systems, to be eventually located in geosynchronous orbit. The LEMUR mobility concepts include inspection and maintenance, and vision-based tool positioning using integrated leg-manipulators, equipped with multipurpose end-effectors. The common characteristics of the two prototypes are summarized in Table 5.

The mobility system consists of 6 legs, including four back legs with 3 DOF's and two front legs with

Dimensions (cm)	20(l) × 15(w) × 10(h)
wheel diameter	6
ground clearance	variable
Mass Total (kg)	1.0
Power Requirements (W)	1.0
Max Speed (cm/s)	3

Table 4: Parameters of the Nano-rover.

Dimensions (m)	4(l) × 2(w) × 1(h)
wheel diameter (m)	2
ground clearance (m)	.5
Mass Total (kg)	20
Power Requirements (W)	18
Max Speed (m/hr)	2000

Table 5: Parameters of the inflatable-wheel rover.

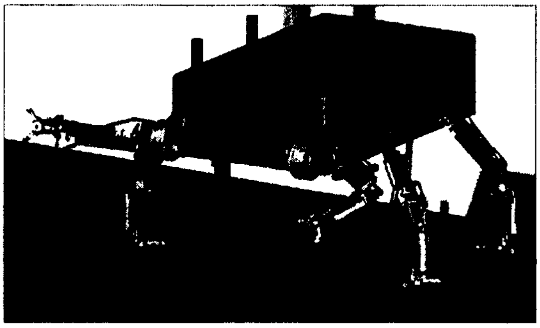

Figure 7: The CAD drawing of the LEMUR legged rover.

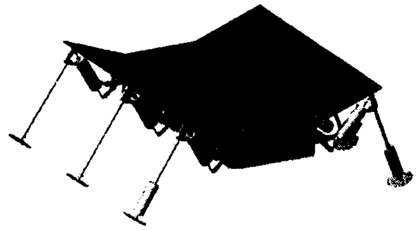

Figure 8: Schematic drawing of the Henry-99 legged rover.

4 DOF's. The front legs are used as manipulators and tool holders. The system is designed to be statically stable using just the rear four legs. The design incorporates energy storage and damping capabilities to enable future tests of dynamic passive stability. The footpad of the two front legs mounts sensor/end-effectors that include: (1) a miniature camera, which can operate as an articulate FootCam for LEMUR and as a miniature microscope on Henry-99, and (2) a rotating footpad tool system, which can support several maintenance tools for the LEMUR demonstration and accommodate a rock grinding end-effector for Henry-99. Legs under development in cooperation with Utah State University and Caltech weigh less than 200 g, including actuation, and are capable of supporting dynamic gaits. Each leg has three DOF's, is capable of lifting at least 500 g, and clears obstacles of about 100-120 mm. The Henry prototype carries also a *watch mast*, about 2 m tall and equipped with a stereo camera to provide a geologist with a eye-level view of the world. Key design features of the mast include a mass of less than 200 g and a deployed height of 1.5 meters.

Experiments are planned with these rovers, especially to verify the energy storage capabilities of the legs, which would enable desirable dynamic gaits, possible more energy efficient than wheels at certain speeds. Furthermore, although the mast employs a stable Double X structure, static and dynamic stability may be affected by the presence of the mast.

Dimensions (cm)	50(l) × 30(w) × 30(h)
leg weight (gr)	200
Ground clearance (cm)	25
Mass Total (kg)	4
Power Requirements (W)	
Max Speed (cm/s)	

Table 6: Common features of the legged rovers.

6 Hopping Rovers

In spite of their many features, wheels and legs have still significant drawbacks from a general mobility point of view. In particular, even inflatable wheeled rovers can only drive over obstacles that are a fraction of the rover's body length. While legged robots can possibly solve this accessibility problem, they are mechanically complex and thus potentially subject to a higher failure rate. Furthermore, both wheeled and legged rovers use many actuators and complex transmission systems. Thus they need larger power supplies and complex control electronics, and have high overall weight. To address these problems, a new generation of minimally actuated devices capable of moving a small science package by hopping is being investigated [4, 7].

Hopping systems for planetary mobility were first proposed in [12, 14] as a promising transportation concept for astronauts in a Lunar environment. In fact, the first order analysis of Lunar hopper performance reported in [9], and summarized in Table 6, shows the advantages of hopping as a mean of transportation in a Lunar environment.

The development of a hopping rover may allow to: (1) minimize the total number of system actuators; (2) minimize the overall size and weight of the entire package so that multiple rovers can be deployed; (3) carry a television camera and some simple on-board scientific sensors; and (4) achieve sufficient mobility to realize some useful scientific capabilities. The simultaneous control of hopping height, hopping direction, hopper stability, and camera pointing is achieved by carrying out sequentially as many operations as possible, instead of simultaneously.

The mobility system of the first hopper prototype consist of a simple linear spring actuated by a motor. The control of the hopper by a single actuator is implemented with the aide of an over-running clutch. With the decoupling action of the clutch, rotation of the motor in one direction drives the leg compression and leg

Mobility	Distance(Km)	Weight(Kg)	Payload(Kg)	Consumes
Hopper	30	450	7	3 hours
Rocket	7	204	7	131 Kg of propellant
Rover	17	1749	larger	several hours

Table 7: Comparison of Lunar Mobility System.

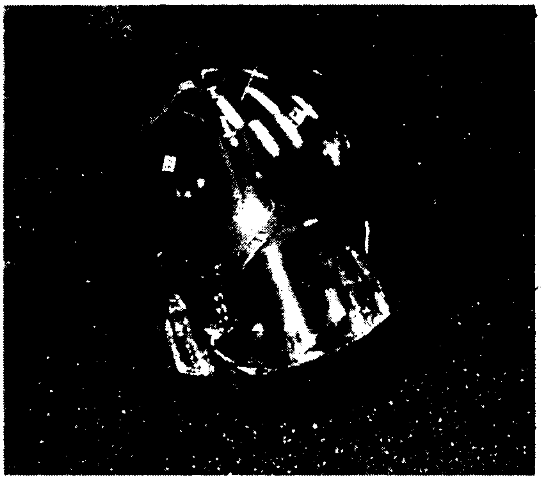

Figure 9: The prototype of the 1^{st} generation hopper.

release subsystem, while rotation in the other direction drives the camera rotation. The orientation of the body can also be modified by rotating the camera, whose off-axis center of mass causes the vehicle to tilt. The self-righting capability is implemented passively in this design by creating a low center of mass. Experiments with this prototype showed that the hopper achieved only about 80 cm of vertical hight, corresponding to a 20% efficiency.

A second prototype was designed to address the problems raised by the first prototype, namely inefficient hopping, unrobust steering, and unrobust self-righting capability, as shown in Figures 10, 11.

To solve inefficiency problem, a combined spring/linkage mechanism was designed. The leg extension is along the vertical y direction. Displacements in the y-direction induce, through the linkage, displacements in the linear spring. In effect, the linkage creates a nonlinear spring from a linear spring. To robustly and accurately point this system in a desired direction, the second generation device employs an active steering mechanism, consisting of a pinion gear that is driven by the primary motor when the leg reaches its maximum compression. Since the hopper will typically land in an unpredictable toppled configuration, an active mechanism is used to bring the mechanism to an upright and stable posture. A two stage self-righting process and self-righting mechanism was designed. During the ***first phase*** of the self-righting process, flaps causing the hopper to roll onto its "back" face. In the ***second phase***, the rotation of a large flap connected to the hopper's back face forces the hopper toward an upright configuration. The second prototype is being tested on a variety of surfaces. It typically jumps a horizontal distance of 70-80 inches, and reaches a vertical height of ~35 inches during free-flight. On Mars, one of the primary opportunities for this vehicle, this performance would translate into a horizontal movement of ~ 20-24 feet and vertical ascent of ~9 feet.

7 Conclusion

This paper presents a brief survey of the main features of planetary vehicles deployed and under development at JPL/Caltech for the exploration of the Solar System. From the "classic" wheel-based configuration, planetary rover design is expanding into several directions, including palm-size nano-rovers, folding/inflatable large rovers, legged and hopping vehicles. Each design responds to the characteristics of specific exploration mission. Nano-rovers are scheduled for asteroid exploration, inflatable rovers are proposed for large areas survey, legged rovers are studied for steep and difficult terrains, and hopping vehicles may be used during coordinated exploration. Tests of the various systems are summarized and results are compared with

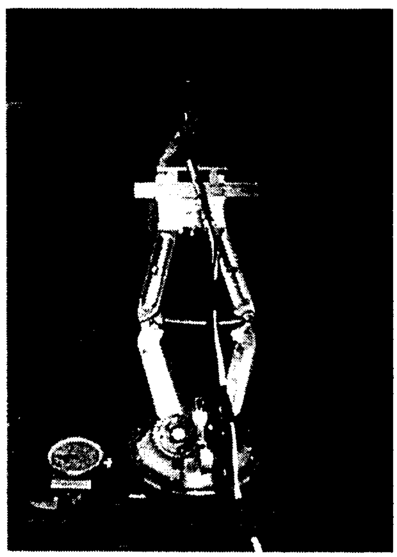

Figure 10: Side view of uncompressed 2^{nd} Generation hopper.

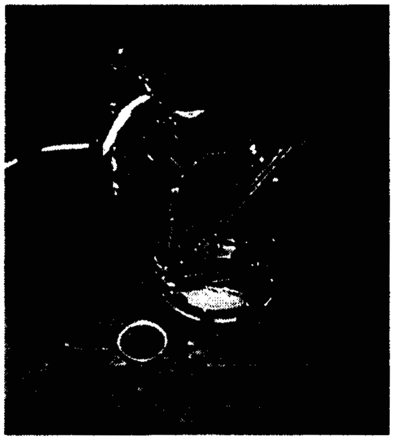

Figure 11: Photo of 2^{nd} Generation hopper in compressed state.

respect to the performance of their mobility system. New designs are expected to emerge depending on specific mission characteristics and technology availability.

Acknowledgments: This research has been carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1] J. Bares, M. Hebert, T. Kanade, E. Krotkov, T. Mitchell, R. Simmons, and W. Whittaker. Ambler: An autonomous rover for planetary exploration. *IEEE Computer*, 22(6):18–26, Aug. 1989.

[2] E. Baumgartner, B. Wilcox, R. Welch, and R. Jones. Mobility performance of a small-body rover. In *Proceedings of the Seventh International Symposium on Robotics with Applications, World Automation Conference, ISORA 16*, Anchorage, Alaska, May 1998.

[3] D. Bickler. A new family of planetary vehicles. In *Proceedings of the International Symposium on Mission technologies and design of planetary mobile vehicles*, Toulouse, France, 1992.

[4] P. Fiorini, S. Hayati, M. Heverly, and J. Gensler. A hopping robot for planetary exploration. In *Proc. of IEEE Aerospace Conference*, Snowmass, CO, March 1999.

[5] E. Gat et al. Beahavior control for robotics exploration of planetary surfaces. *IEEE Transaction on Robotics and Automation*, 10(4):490–503, 1994.

[6] K. Goodall. Web site: http://mars.jpl.nasa.gov/2001/rover. Aug. 1999.

[7] E. Hale, N. Schara, J. Burdick, and P. Fiorini. A minimally actuated hopping rover for exploration of celestial bodies. In *Proc. of IEEE International Conference on Robotics and Automation*, San Francisco, CA, April 2000. (Submitted).

[8] J. Jones. Web site: http://robotics.jpl.nasa.gov/tasks/inflrovers. Aug. 1999.

[9] M.H. Kaplan and H. Seifert. Hopping transporters for lunar exploration. *J. Spacecraft and Rockets*, 6(8):917–922, Aug. 1969.

[10] A. Mishkin, J. Morrison, T. Nguyen, H. Stone, and B. Cooper. Operations and autonomy of the mars pathfinder microrover. In *IEEE Aerospace Conf.*, 1998.

[11] A. Mishkin, J. Morrison, T. Nguyen, H. Stone, B. Cooper, and B. Wilcox. Experiences with operations and autonomy of the mars pathfinder microrover. In *Proc. of 1998 IEEE Aerospace Conference*, SnowMass, CO, March 21-28 1998.

[12] J. Oberth. *The Moon Car.* Harper and Brothers, New York, 1959.

[13] P. Schenker. Web site: http://robotics.jpl.nasa.gov/tasks/etrover. Aug. 1999.

[14] H.S. Seifert. The lunar pogo stick. *Journal of Spacecraft and Rockets*, 4(7):941–943, July 1967.

[15] H. Stone. Mars pathfinder microrover a low-cost, low-power spacecraft. In *Proc. of AIAA Forum on Advanced Developments in Space Robotics*, Madison, WI, August 1996.

[16] E. Tunstel, R. Welch, and B. Wilcox. Embedded control of a miniature science rover for planetary exploration. In *Proc. of the 7th International Symposium on Robotics with Applications, WAC'98*, Anchorage, Alaska, May 1998.

[17] R. Volpe. Navigation results from desert field tests of the rocky 7 mars rover prototype. *International Journal of Robotics Research*, May 1999.

[18] R. Volpe, J. Balaram, T. Ohm, and R. Ivlev. Rocky 7: A next generation mars rover prototype. *Journal of Advanced Robotics*, 11(4), December 1997.

[19] C. Weisbin, G. Rodriguez, P. Schenker, H. Das, S. Hayati, E. Baumgartner, M. Maimone, I. Nesnas, and R. Volpe. Autonomous rover technology

for mars sample return. In *Proceedings of the International Symposium on Artificial Intelligence, Robotics, and Automation in Space (i-SAIRAS '99)*, Noordwijk, The Netherlands, June 1-3 1999.

[20] R. Welch. Web site: http://robotics.jpl.nasa.gov/tasks/nrover. Aug. 1999.

[21] R. Welch. Web site: http://www.jpl.nasa.gov/facts/muses.pdf. Aug. 1999.

[22] B. Wilcox et al. Computer aided remote driving. In *Proc. of AUVS-86*, Boston, MA, 1986.